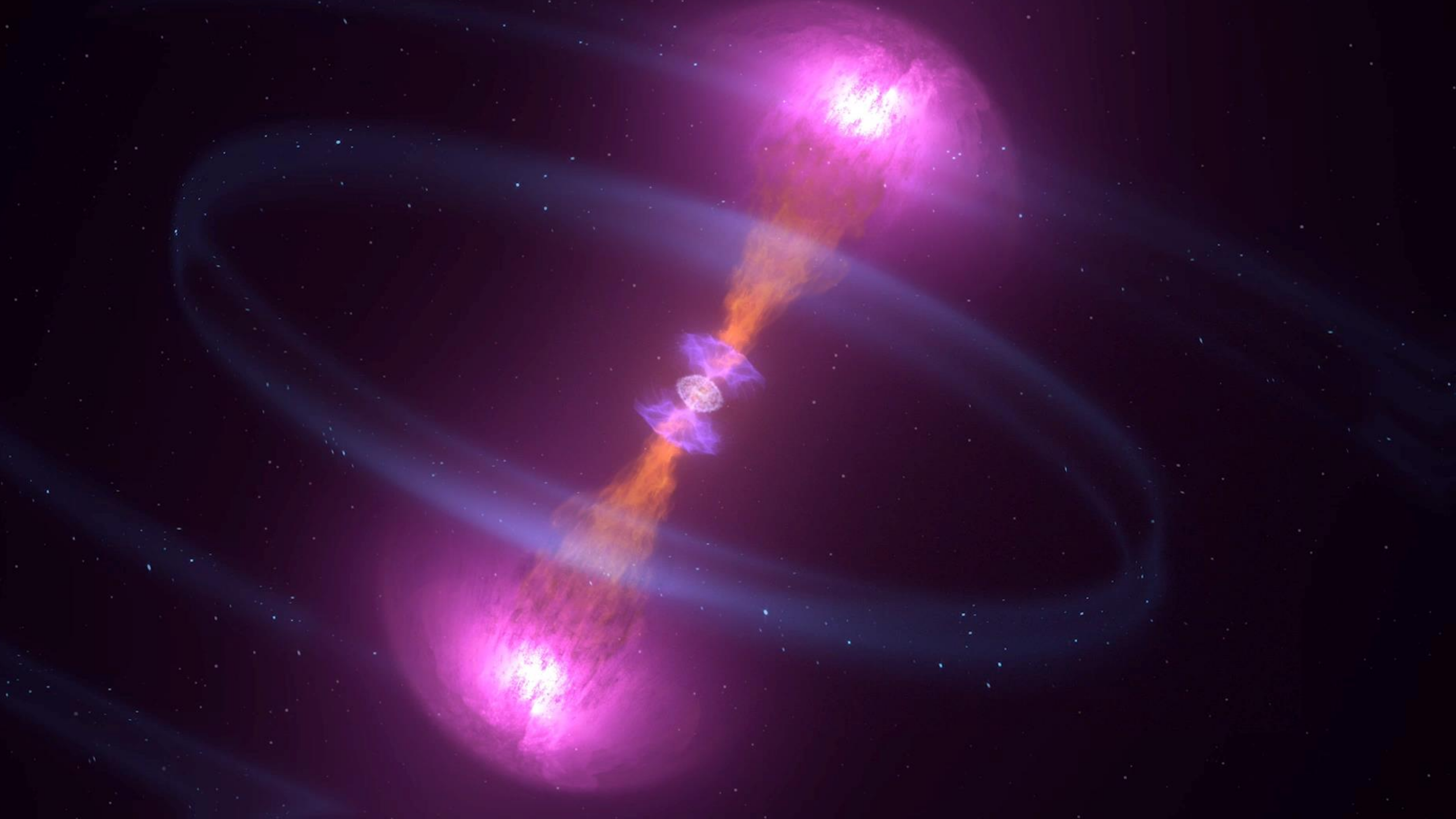
How to make speed of light jets

Eric Burns

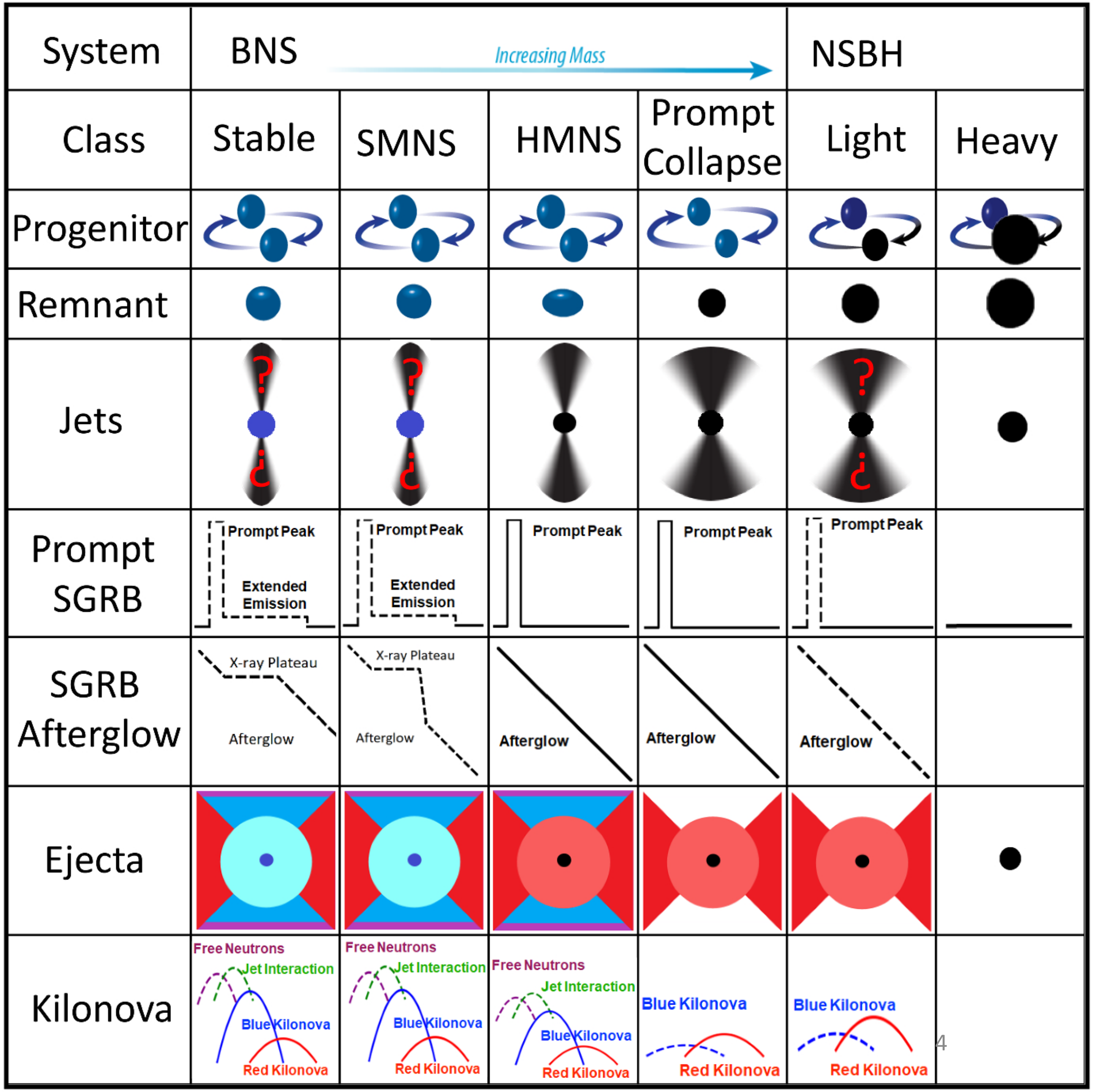
Steps to an ultrarelativistic jet

1. Create the compact remnant
2. The remnant and angular momentum as a central engine
3. Jet launch in the baryon-poor polar regions
4. Jet propagation through the surrounding material
5. Gamma-ray burst?



Central Engines

- Hyper-accreting black hole or magnetar?
- Hidden in collapsars, exposed in neutron star mergers
- EM-dark NSBH mergers
- Also GW-GRB time delay



Jet launch mechanism
-3 options (2 BH, 1 NS)

BH: Discriminate between Blandford-Znajek* and neutrino-antineutrino annihilation

- Efficiency
- Accretion timescale

Salafia and Giacomazzo 2021 A&A 645

$$\eta \sim E_{K,\,\mathrm{jet}}/M_{\mathrm{disc}}c^2 \sim 10^{-3}$$

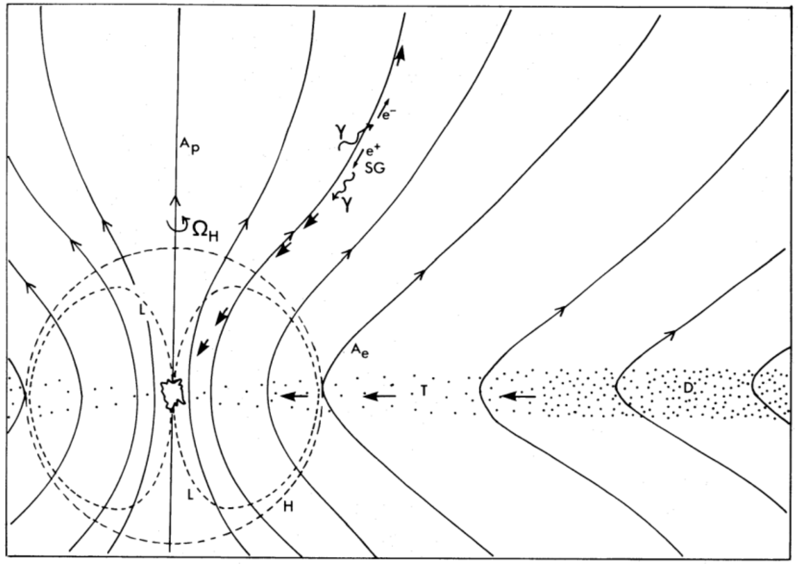
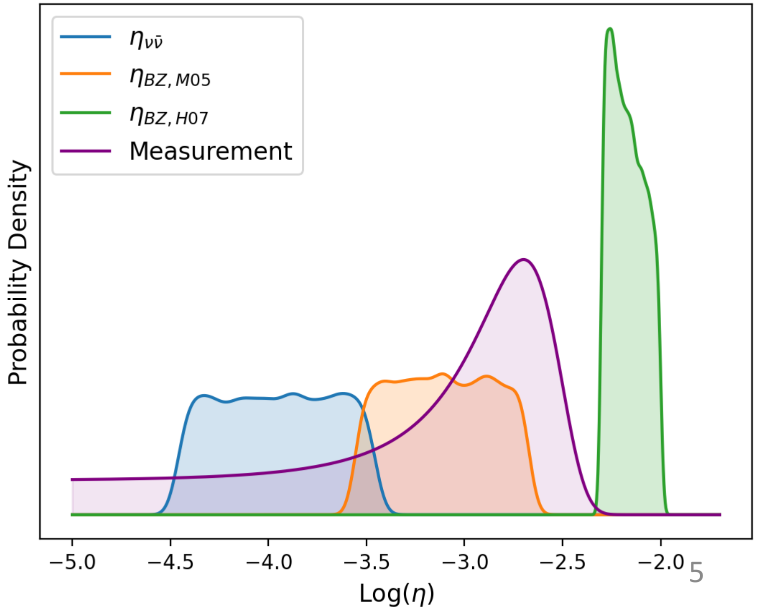
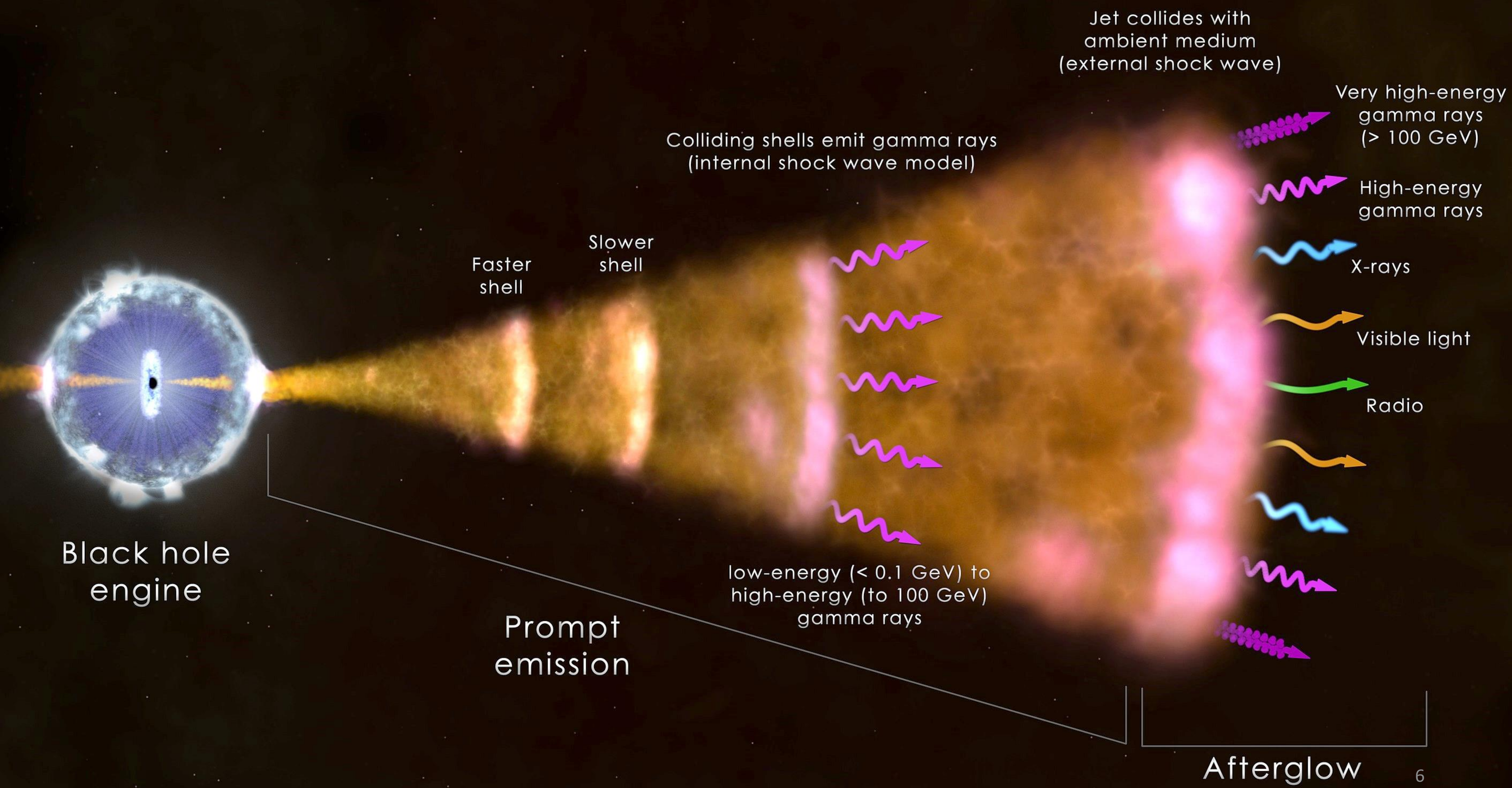


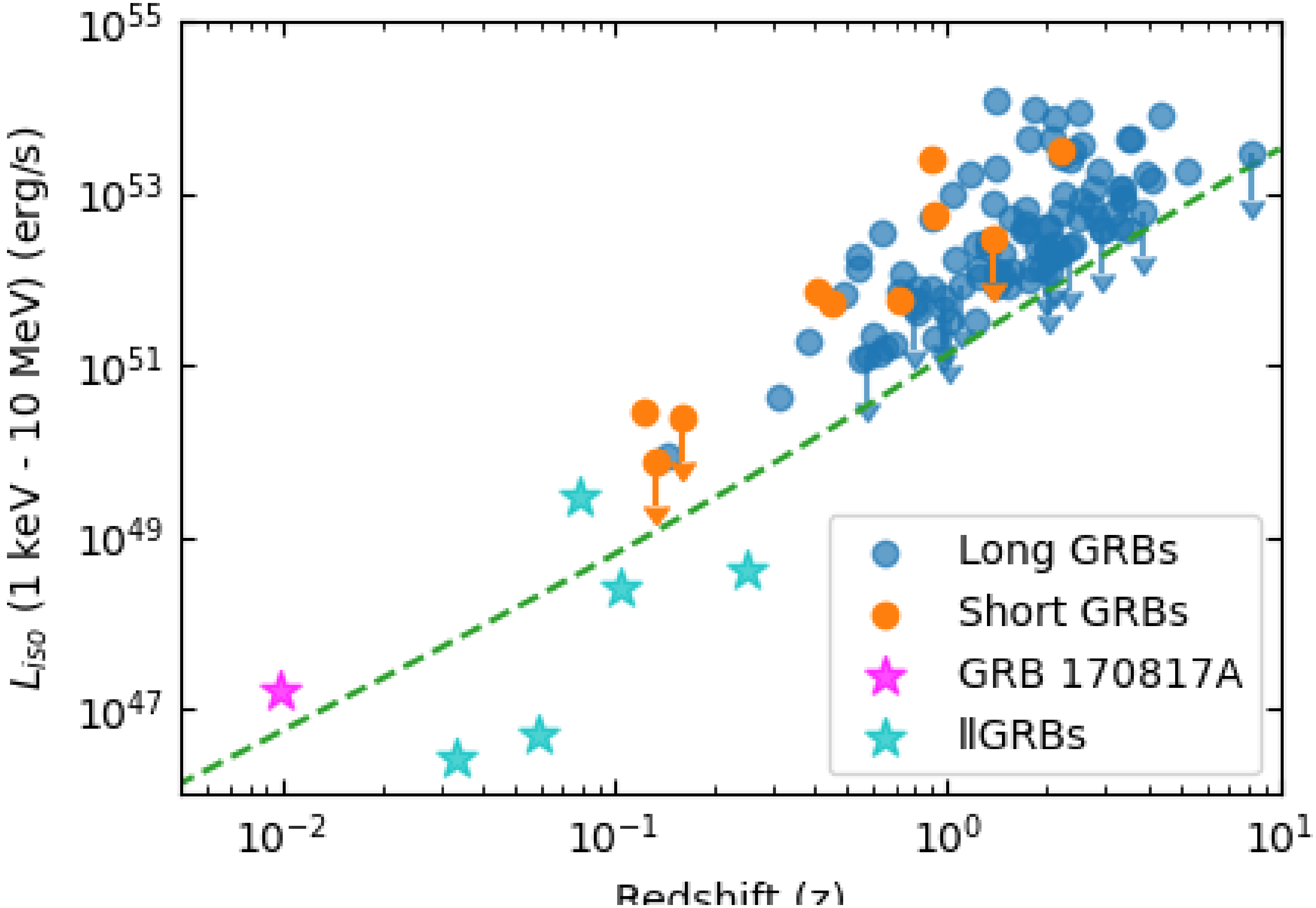
Figure 1. Schematic cross-section of black hole and magnetosphere, using r and θ coordinates in normal way. (Due to axial and time symmetry the diagram is independent of the azimuthal and time coordinates that are being held constant; these can be the Kerr coordinates v and $\tilde{\phi}$, or for $r > r_+$ the Boyer–Lindquist coordinates t and ϕ.) The poloidal field has been chosen so that $\mathbf{\Omega_H \cdot B} > 0$. H is the

NS: has to be a magnetar, driven by the extreme magnetic fields

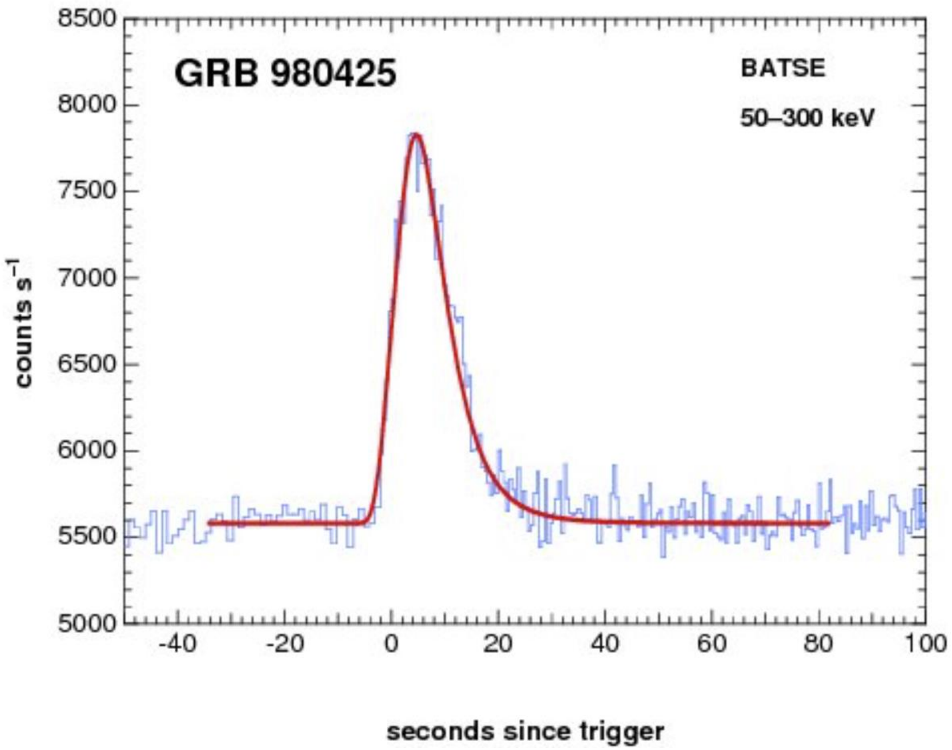



Jet collides with
ambient medium
(external shock wave)
Very high-energy
gamma rays
(> 100 GeV)
Colliding shells emit gamma rays
(internal shock wave model)
High-energy
gamma rays
Slower
shell
Faster
shell
X-rays
Visible light
Radio
Black hole
engine
low-energy (< 0.1 GeV) to
high-energy (to 100 GeV)
gamma rays
Prompt
emission
Afterglow

Jet propagation - low-luminosity gamma-ray bursts

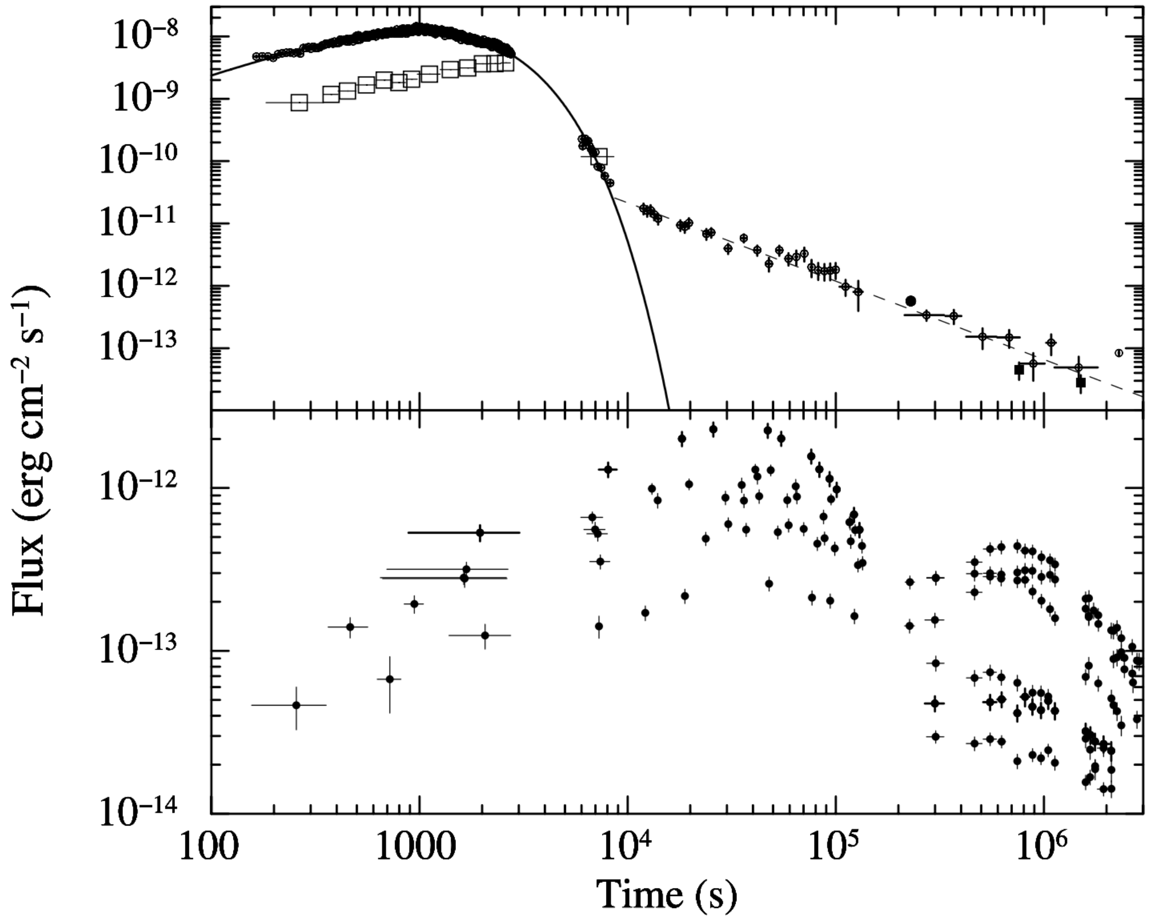


Modified from J. Racusin

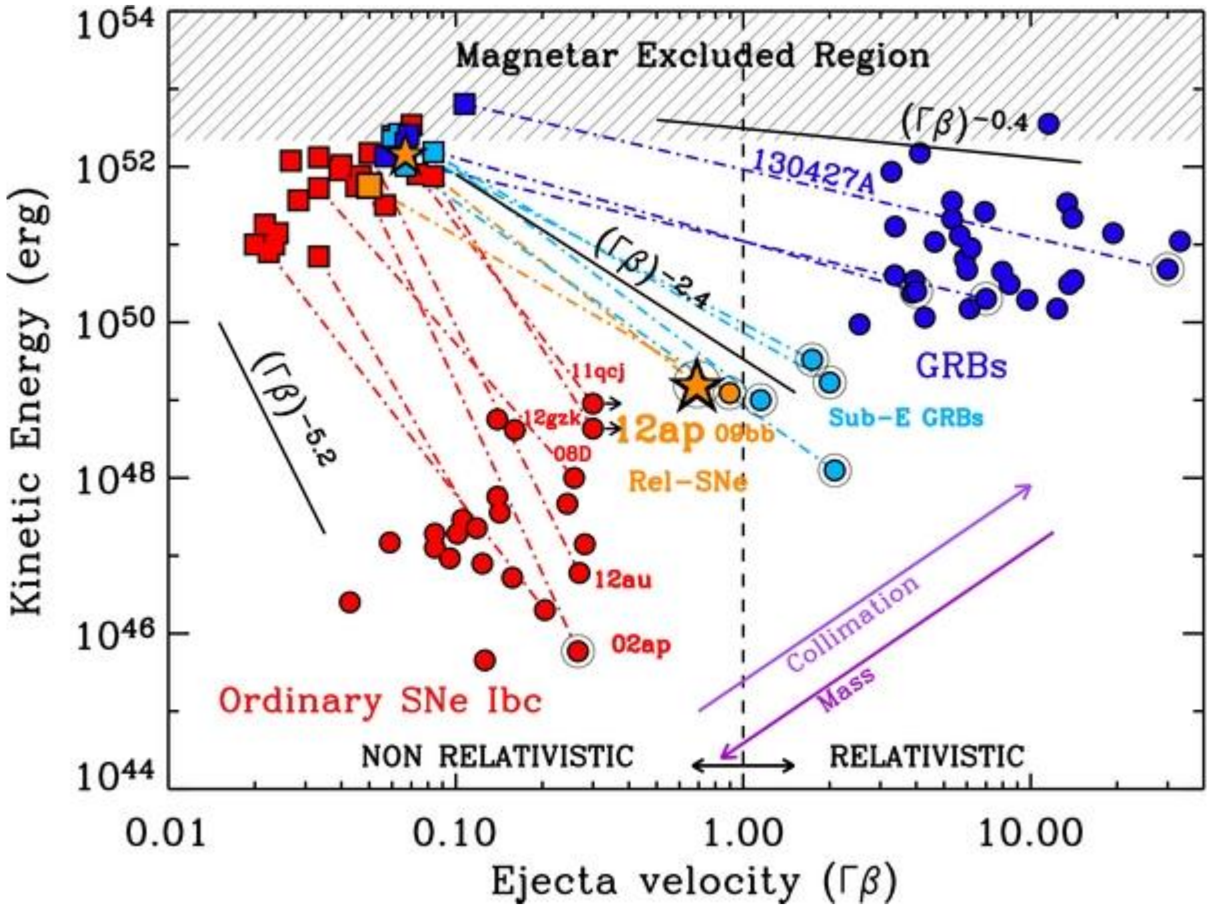


Dar 2005

Jet propagation - relativistic supernova make a continuum

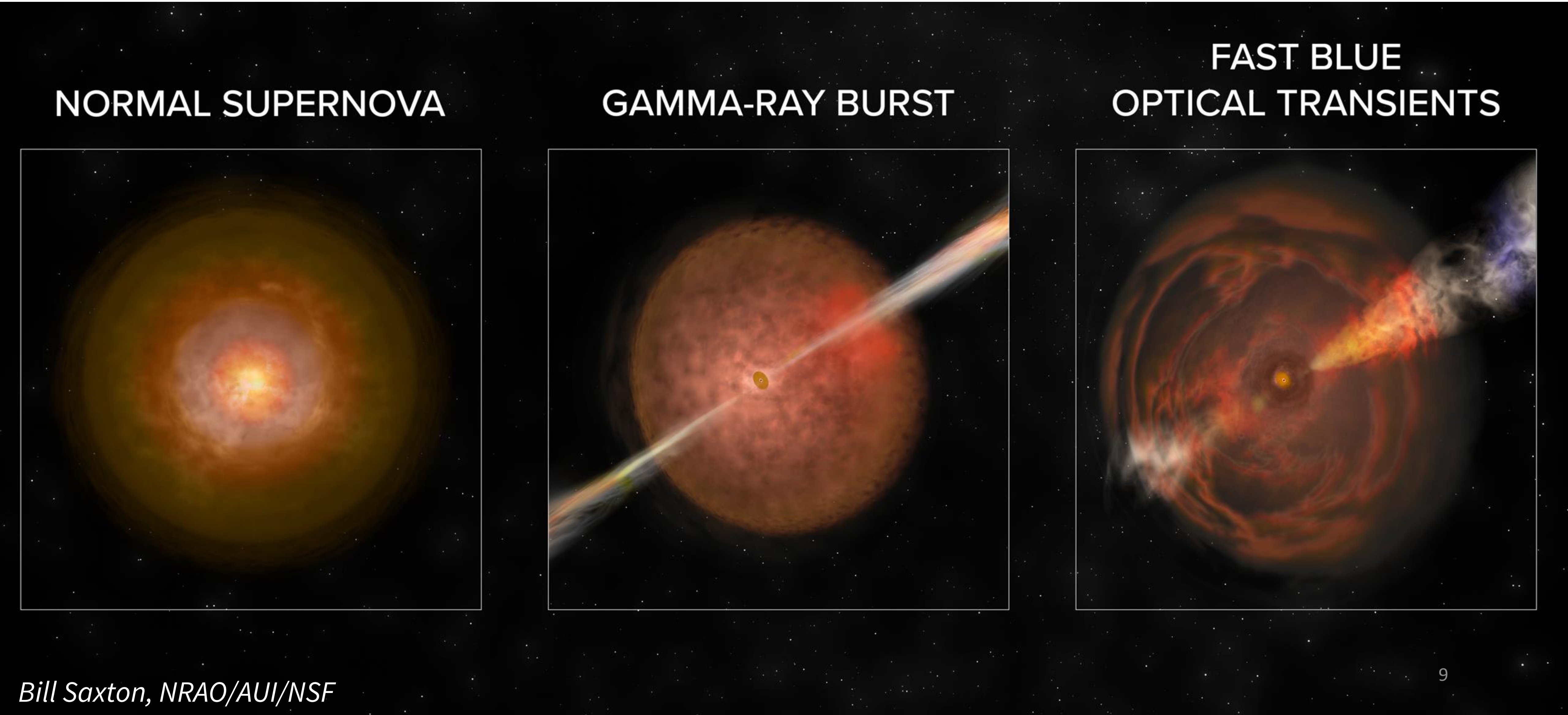


XRF 060218 Soderberg et al. Nature 2006



Margutti et al. 2014 ApJ 797 107

Jet propagation - Fast Blue Optical Transients



Bill Saxton, NRAO/AUI/NSF

Jet propagation - Choked GRBs and neutrinos

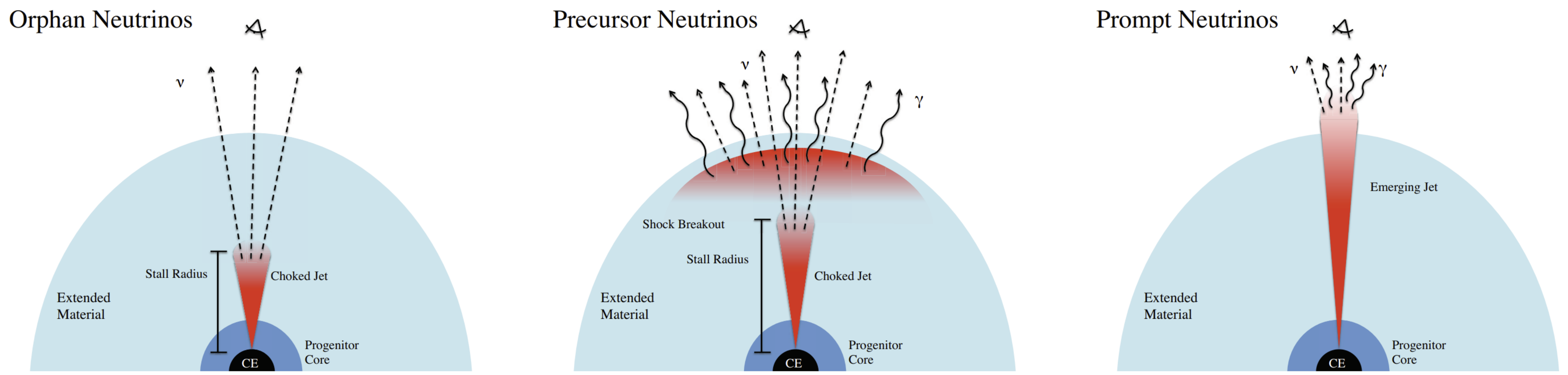


FIG. 1: **Left panel:** The choked jet model for jet-driven SNe. Orphan neutrinos are expected since electromagnetic emission from the jet is hidden, and such objects may be observed as hypernovae. **Middle panel:** The shock breakout model for LL GRBs, where transrelativistic shocks are driven by choked jets. A precursor neutrino signal is expected since the gamma-ray emission from the shock breakout occurs significantly after the jet stalls (e.g., [26]). **Right panel:** The emerging jet model for GRBs and LL GRBs. Both neutrinos and gamma-rays are produced by the successful jet, and both messengers can be observed as prompt emission.

Steps to an ultrarelativistic jet

1. Create the compact remnant
2. The remnant and angular momentum as a central engine
3. Jet launch in the baryon-poor polar regions
4. Jet propagation through the surrounding material
5. Gamma-ray burst?

Advancing our understanding this decade

All of this relies on advances in modeling of supernova, kilonovae, neutron star mergers, etc, and all of the input physics

- Why
  - Origin of elements, neutrinos, GWs, and more
  - Particle acceleration from mildly to ultrarelativistic
  - Tests of fundamental physics
- How
  - Detect, identify, and localize transients from their earliest detectable signals
    - High energy
  - Signals across the EM spectrum and in other messengers provide complementary diagnostics
    - Nearby events are key (see SN 1987A, GW170817, GRB 980425, etc)
  - Ensure observations of externally identified signals (e.g. Rubin relativistic transients)
    - Non-detections matter

With immediate broadband follow-up

As outlined in the Decadal

- 7.5.3.1

While ground-based measurements by observatories large and small are essential, several key capabilities that must be sustained to enable time-domain and multi-messenger astrophysics can only be realized in space. The most important of these are wide-field gamma-ray and X-ray monitoring, and rapid and flexible imaging and spectroscopic follow-up in the X-ray, ultraviolet (UV), and far-infrared (far-IR).

- J.5.1

Space-based platforms provide access to those bands that are undetectable from the ground: gamma-rays, X-rays, ultraviolet, and the mid- to far-IR. Historically, these bands have proven crucial to transient event detection, as well as event characterization and classification. A future system needs to include the following features: (1) detection capability at X-ray/gamma-ray energies with near 4π sr coverage; (2) prompt event localization at the few arcsecond level or better; (3) rapid-slewing for follow-up imaging and spectroscopy at X-ray, ultraviolet, and IR wavelengths; (4) long-term monitoring in these same bands; and (5) a data system capable of issuing fast alerts to the community with all essential information.

Rather than advocate for a specific mission in this field, the panel suggests instead that NASA create a coordinated strategic program in time-domain astrophysics that provides the capabilities described above, potentially capitalizing on the international missions that are operational. These could be

A true all-sky high energy monitor

Capabilities

- 4pi
- Long, contiguous livetime
- ~1 keV – 10 MeV
- ~10’ localizations
  - At least in X-rays
- **Prompt alerts**

Detection or full coverage of every

- Supernova (optical, MeV neutrinos, GWs)
- Gamma-ray burst
- High energy neutrino
- Magnetar
- Tidal disruption events
- Time-domain monitoring of the entire bright X-ray sky
- **Rare and surprise transients**

- What are or will be the most pressing scientific questions for TDAMM in the next several years?
  - What separates CCSN from gamma-ray bursts?
  - The origin of high energy neutrinos?
  - All of the neutron star merger science
- Which capabilities (top level) are needed to address them?
  - 4pi X-ray monitors with large contiguous livetime intervals
- How well does the current mission fleet address them?
  - It doesn't capture emission from the 'missing' link of nearby X-ray events
- Which avenues of inquiry will be most ripe for discovery in the next few years?
  - Build the Decadal-recommended NASA TDAMM Program in a coherent manner
- What collaboration between the ground and space can be done to maximize the science?
  - All-sky high energy monitor partnered with IceCube and Rubin (and friends)

Backup

Rates and the origin of neutrinos

- llGRBs ~10^2-10^3 $Gpc^{-3}yr^{-1}$
  - For comparison, lGRBs ~10^{-1}-10^0; CCSN ~10^5

Murase et al. 2019 PRL 123

- <u>~1 high-energy neutrino detection</u>
  - IceCube Gen 2: Nominal improvements begin 2030, full upgrade 2037
    - <300 Mpc; 10-100/yr
  - IceCube: Now, ~5x less sensitive than Gen 2
    - 130 Mpc; 1-10/yr
- Then why haven't we seen them already?
  - Association ∝ R_{signal} * Δt * (Ω/4π) where Ω is the worse localization solid angle
    - Optical SNe and neutrinos: Δt ~ 10^6 s, Ω ~0.01, R_{signal} ~ 10^2 gives ~2 sigma evidence
    - <u>SNe SBO and neutrinos: Δt ~ 10^2, Ω ~0.01, R_{signal} ~ 10^2 gives >5 sigma every time</u>

Non-EM messengers will generally have limited spatial precision, so time is absolutely critical for robust association and all multimessenger science